

The Contaminant Footprint of Landed Spacecraft: Toward an Inventory and Modelling Framework

Dr. William A. Hoey^{1*}; Carlos E. Soares¹; Dr. John M. Alred²

With contributions from JPL JVSRP fellows P. Guterrez Cascales and R. Alves Hailer.

*) william.a.hoey@nasa.gov

1. Amentum Space Missions Division, JETS II Contract, Houston TX.
2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.



Understanding ‘Contamination’ in Airless Environments

How can we quantify the “organic contaminant footprint” of a landing vehicle?

A Planetary Protection (PP) Organic Inventory and Archiving Workshop was held at NASA HQ in Feb. 2024 in which **molecular contamination topics** were explored to ([per the Workshop site](#)):

- *Evaluate the current organic inventory and archiving requirements in NASA PP policy.*
- *Provide a modernized, updated scientific and engineering-balanced rationale and approach to capturing molecular contamination to enable current and future science investigations.*
- *Identify knowledge gaps or additional policy inconsistencies that need to be addressed.*

Source terms and processes relevant to organic molecular contamination on the lunar surface were described based on NASA flight project engineering experience (Mars 2020, Europa Clipper...)

- *Examples include materials outgassing, venting from uncrewed and crewed systems, propulsion...*

Q: If a combination of source terms can be described for an asset on the lunar surface – for instance, a landed spacecraft – **how can we understand the “organic contamination footprint” of that asset?**

- *E.g., Where does molecular contamination transport and deposit – is this local or at lunar scale?*

This talk investigates key organic source and transport vectors and how they can be modeled.

The Contaminant Footprint of Landed Spacecraft

The “footprint” of a lunar surface asset – its contributions of organic molecular contaminant to the lunar environment inclusive of release, transport, loss, and deposition processes – encompasses:

1. **Source terms**: high-level inventory of organic contaminants released by lunar surface assets.
 - *Common materials used on such vehicles and their available outgassing characterizations, &*
 - *Common propulsion systems used on such vehicles and their primary plume byproducts, &*
 - *Common modes and quantities of vented material, e.g., through passivation, ECLSS, etc.*
2. **Loss terms**: high-level models for loss processes relevant to species of organic contaminant.
 - *Photodissociation and ionization; related surface chemistry;*
 - *Gravitational or thermal escape (loss of molecules to space); &*
 - *Adsorption / desorption onto the lunar surface and permanent deposition into ‘cold traps’ like PSRs.*
3. **Transport terms**: a **probabilistic free molecular transport model** for organic molecules from release and their first contact with the lunar surface until their loss, that can compare and report on each generation and loss process (i.e., which are driving, and for which class of vehicle?)
 - Examples of RGD/FM frameworks for, e.g., water transport in lunar landings have been published by [Prem et al. 2020](#) and [Farrell et al. 2024](#), and recently also for methane by [Paiva and Sinibaldi \(2025\)](#).

See also: Hoey, W., Soares, C., 2024. “Engineering Models: Thruster Plume-Surface Interactions, Landing Site Alteration, Organic Footprint and Acceleration / Dispersion of Dust and Regolith,” Invited presentation, NASA Office of Planetary Protection Organic Inventory Workshop. [Link](#)

Repurposed from “**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**,” by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. <https://doi.org/10.48577/jpl.QCQ97L>

Source Terms: Outgassing

Material outgassing is a predominant source of molecular contamination in vacuum.

Example **receiver** surface onto which adsorption occurs

$$\text{Adsorption/ Desorption: } \frac{dm}{dt} = \frac{m}{\tau_{ads}} \frac{E_{A,ads}}{RT}$$

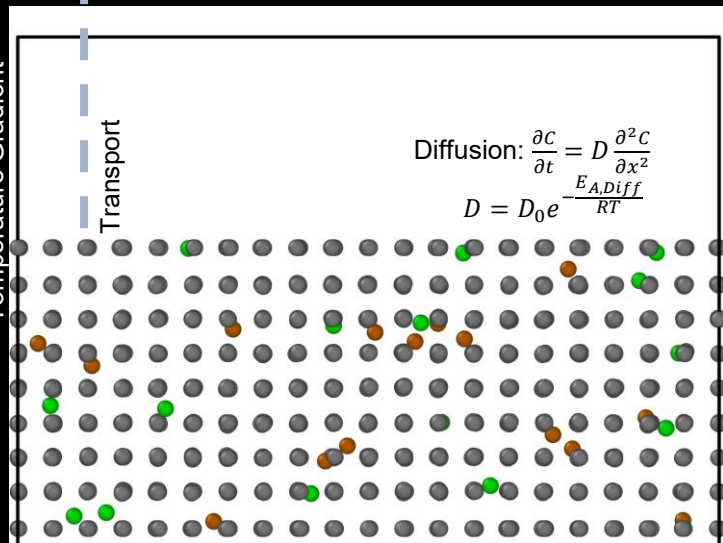
$$\tau_{ads} = \tau_0 e^{-\frac{E_{A,ads}}{RT}}$$

$$\text{Diffusion: } \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$$

$$D = D_0 e^{-\frac{E_{A,Diff}}{RT}}$$

Energy Gradient
Temperature Gradient

Transport



Figures by co-author J. Alred, derived from: Alred, J., et al. 2024. "Outgassing Contaminant Species Extraction, Characterization and Modeling," Invited presentation to the NASA Office of Planetary Protection - Planetary Protection Organic Inventory Workshop. See also: [DOI](#)

Mars 2020



Alred, J., Martin, M., Hoey, W., et al., 2020. Proc. v. 11489, SPIE Systems Contamination; 1148904. [DOI](#)

Mission: Sampling Mars with objectives to detect organic signatures
Instrument: Returned samples, multiple instruments
Threat: Outgassing contaminants condensing within sample tubes could jeopardize detection

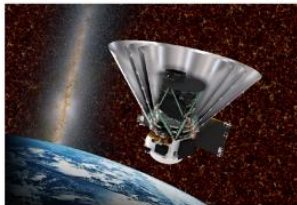
Mars Sample Return



Alred, J., Martin, M., Hoey, W., Soares, C., 2024. NASA Office of Planetary Protection - Planetary Protection Organic Inventory Workshop. [NASA VPIN Link](#)

Life detections instruments require understanding of contamination chemical constituents to guarantee unambiguous detection

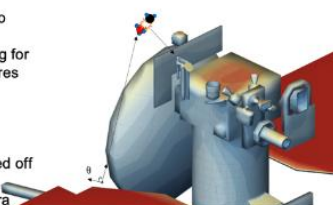
SPHEREx



Alred, J. et al., 2021. Proc. IEEE Aerospace Conference. [DOI](#)

Mission: Scientific objectives to image biogenic molecules in the universe
Instrument: Optical characterization
Threat: Water and other biogenic molecules outgassing condensing in telescope causes severe attenuation of throughput

Europa Clipper



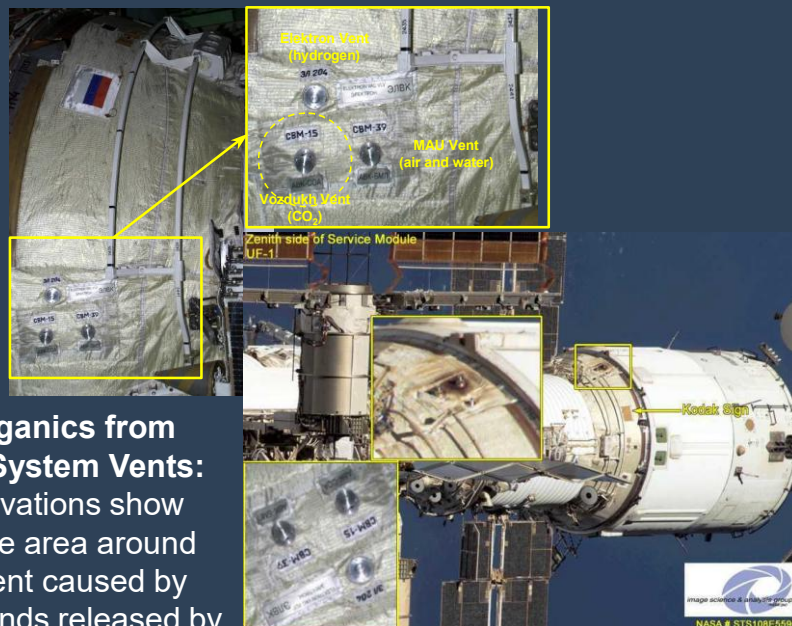
Soares, C., Hoey, W., Anderson, J., Ferraro, N., 2019. Proc. 70th Int'l Astronautical Cong. IAC-19-D5.3.12.x50567. [DOI](#)

Mission: Objectives to sample Europa's atmosphere, including for organics / biosignatures
Instrument: Mass spectrometer
Threat: Outgassing contaminants reflected off atmosphere induce spurious mass spectra

Source Terms: Venting

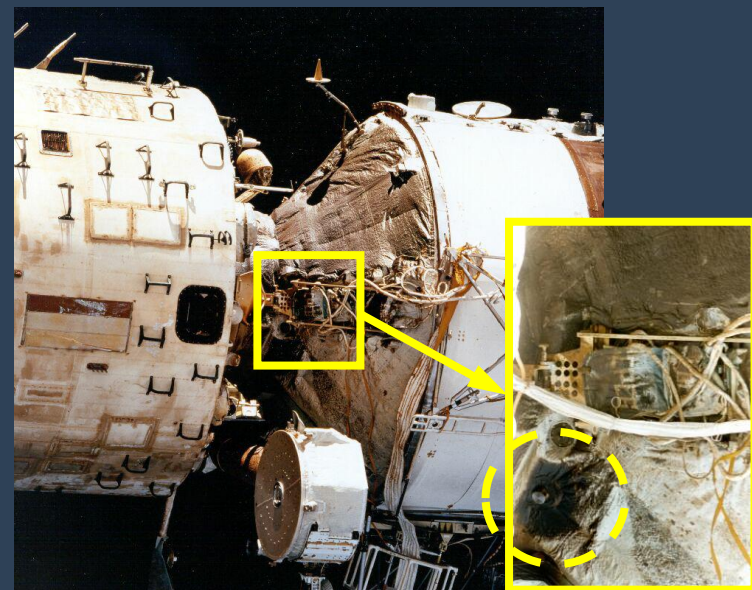
Crewed vehicles release high amounts of organic contaminant from venting systems.

Figures by co-author C. Soares, derived from: Soares, C. 2024. "Organic Contamination From Venting and Leakage (Environmental Control, Life Support Systems, IVA Science and Spacecraft Systems) - The ISS Experience," Invited presentation to the NASA Office of Planetary Protection – PP Organic Inventory Workshop. [See also: our RGD 33 talk!](#)



Release of Organics from Life Support System Vents:

‘On-orbit observations show darkening in the area around the Vozdukh vent caused by amine compounds released by the CO₂ scrub system.’



‘The Mir Space station had the highest recorded levels of **organic contamination** from vacuum venting causing >10,000 Angstrom depositions and impacts to thermo-optical properties.’

Source Terms: Engine Plumes

Spacecraft descent engine and attitude control thruster plumes generate gas- and liquid-phase contaminants that can alter landing and science-sampling environments.

- We have applied RGD and empirical methods to simulate plume effects, including experimental materials compatibility and plume testing with DLR.

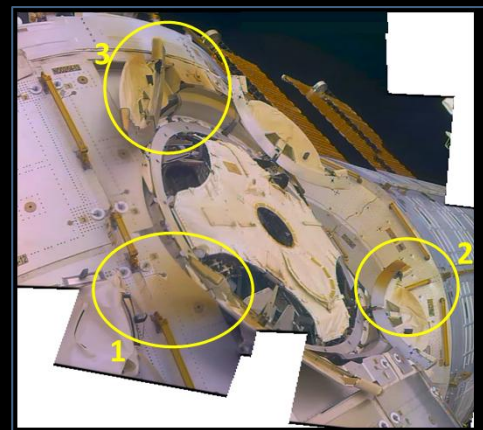


DLR STG-CT Facility. Image credits: DLR

Plume free expansion computed with CFD/DSMC.
Image credit: JPL JVS RP fellow Antonietta Conte.



DLR STG-CT test section; thruster pack at center.
Image credit: DLR



See also: Hoey, W., Soares, C., 2024. "Engineering Models: Thruster Plume-Surface Interactions, Landing Site Alteration, Organic Footprint and Acceleration / Dispersion of Dust and Regolith," Invited presentation, NASA Office of Planetary Protection Organic Inventory Workshop. [Link](https://doi.org/10.48577/jpl.QCQ97L)

Examples of Vehicle Self-Pluming Analyses

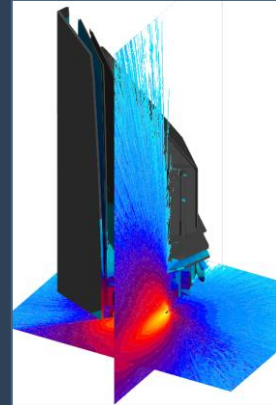
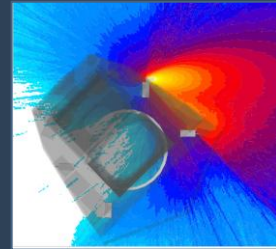
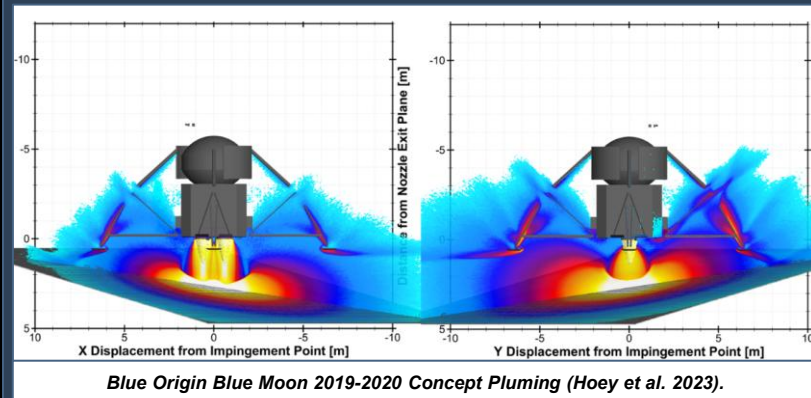
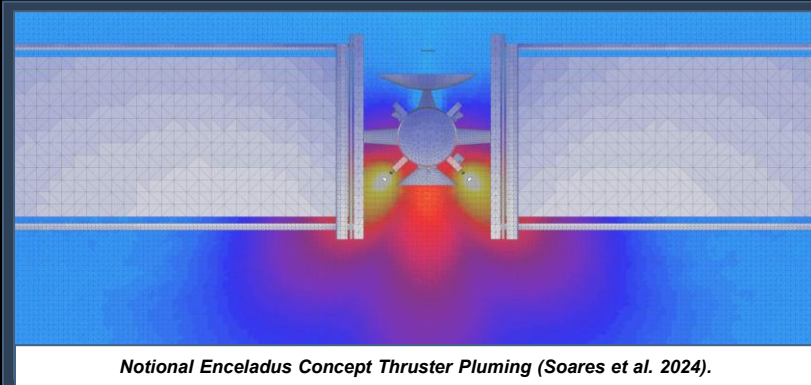
Hoey et al. have investigated **vehicle self-pluming** for in-space and landing applications with CFD/DSMC methods:

- *Moon*: Blue Origin Blue Moon concept (Hoey et al. 2023) and a CLPS lander.
- *Europa*: a Europa Lander concept (Lam et al. 2019, Hoey et al. 2020).
- *Enceladus*: Enceladus concepts (ex. figure at right from Soares et al. 2024).
- *In-space: Near-Earth Object Surveyor*.

We have extended models for inert particle transport in lunar landing & launch depressurization environments to study microorganism transport.

Hoey, W., Martin, M., Alred, J., Soares, C., Ababneh, M., 2023. "Analyses of Blue Origin Blue Moon Lunar Landing Descent Engine Plume Effects," Proc. 52nd International Conference on Environmental Systems (ICES); no. 42. [HDL](#)

Soares, C., Hoey, W., Wong, A., Anderson, J., Grabe, M., 2024. "Experimental Characterization of Spacecraft Thruster Plume Contaminant Composition for Enceladus Orbiter and Lander Mission Concepts," 55th Lunar and Planetary Science Conference (LPSC). [Link](#)



Near-Earth Object Surveyor Single-Engine Pluming Example

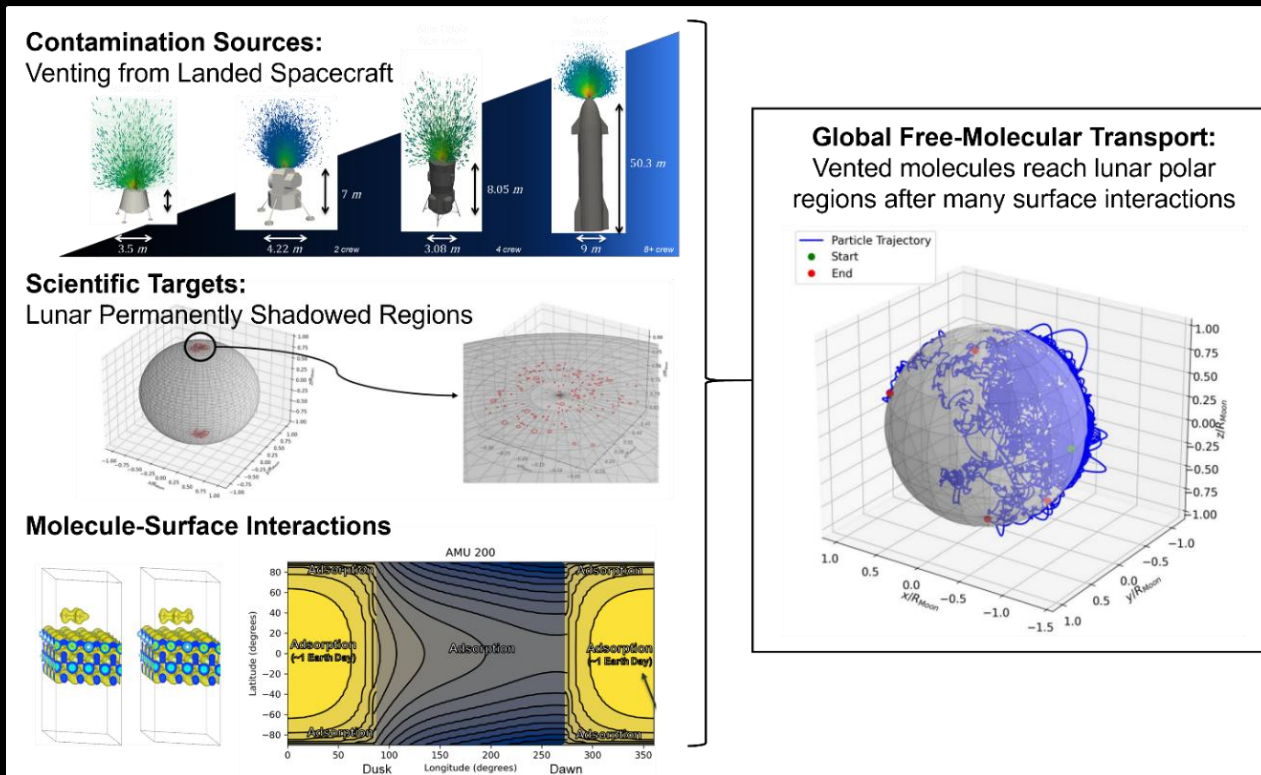
All example charts show normalized contours of pressure and are examples of one-way-coupled CFD/DSMC approaches.

Comparing and Contrasting Source Terms

Hoey, W., et al. "The Contaminant Footprint of Landed Spacecraft: Toward A Modeling Framework." Manuscript in draft.

	Materials Outgassing	Chemical Propulsion System Plumbing	Venting Uncrewed Systems, e.g., Passivation	Venting Crewed Systems: e.g., ECLSS, Airlock Cycling
Contaminant Phase	<u>Molecular</u>	Primarily <u>molecular</u> May contaminate regolith <u>particulate</u> , may release <u>droplet</u> or <u>soot</u> products	<u>Molecular</u> <u>Droplet or particulate waste</u>	<u>Molecular</u> <u>Droplet or particulate waste</u>
Driver of Total Source	Vehicle dry mass of nonmetallic and vacuum-exposed materials	Vehicle propellant mass (fuel and oxidizer), as used in descent, landing, and ascent operations	Unspent vehicle propellant mass ejected at end-of-life; ejected waste from instrument or vehicle processes	Total crew count and duration of operations on the solar system body
Nature of Release	Spontaneously and gradually while exposed to vacuum; could span years	Continuous periods of engine firing in descent, landing, and ascent; could span minutes-to-hours	Discrete events to deplete reservoirs, each could span seconds-to-minutes.	May include continuous gas-phase venting from ECLSS, discrete airlock cycling events, or ejections of waste
Rate of Contaminant Release	Driven by local temperatures; time of vacuum exposure; material selection and pre-conditioning.	Driven by total thrust, therefore by vehicle total mass during descent, landing, and ascent operations	Open-ended; driven by the design, requirements, and operation of venting systems	Driven by crew count and mission duration (ECLSS) and operations (EVAs, waste ejections, etc.)
Organic Contaminants?	Typical spacecraft materials will contain some organic molecules that outgas in near-vacuum	Generated as combustion products, dependent on propellant choice and engine operation	May be present in vented propellant and instrument or vehicle waste	Present in ECLSS venting, cabin atmospheres and crew waste
Potential Mitigations of Organic Component	Standard approaches exist for sensitive missions – material screening and selection of low-organic-outgassing materials; pre-conditioning of materials and spacecraft with bake-outs	Unlikely – could relate to choice of propellant, engine firing modes, landing site selection	Mission-dependent – vehicles could plan to retain or scrub certain waste	Mission-dependent – vehicles could plan to retain or scrub certain waste

Modeling Long-Distance Free Molecular Transport



Modeling Global Free-Molecular Transport for Organic Molecules

(Top Left): Molecular contaminants vented from lunar landed spacecraft are simulated with DSMC.

(Center Left): Lunar permanently shadowed regions (PSRs) of high science and ISRU value are modeled as sinks for contaminant.

(Bottom Left): Simulations of molecular-surface interactions, combined with a time-variant lunar surface map, provide insight into the residence time of certain *n*-alkane species on the lunar surface.

(Right): In combination, these elements are incorporated into a simulation for the transport of organic molecular contaminant from a landing site to distant regions of the Moon.

Venting analyses and figures by JPL JVS RP P. Gutierrez Cascales, 2024.

Lunar-scale free molecular transport analyses and figures by JPL JVS RP R. Alves Hailer, 2024.

See also: Hoey, W., Anderson, J., Alred, J., Soares, C., Gutierrez Cascales, P., Alves Hailer, R. "Modeling the Contaminant Footprint of Spacecraft Operating in Near-Vacuum." 56th Lunar and Planetary Science Conference, The Woodlands, TX; Mar. 2025. [Link](#)

Conclusions and Discussion

- **Spacecraft alter their environments** and may compromise their engineering or science objectives as they generate and disperse contaminant (inert or biological).
 - *This is never more true than during landings and surface operations!*
- **Engineering models** for spacecraft outgassing, venting, and engine pluming processes can be helpful in characterizing contaminant environments.
 - *Spacecraft designs are already directly informed by such models in order to mitigate threats of contamination, heating, chemical or mechanical erosion, etc.*
- **Established tools exist** for some gas-dynamic problems in engineering:
 - *These tools are being extended to study effects beyond the immediate landing environment and vehicle, i.e., the transport of organic outgassing, venting and plume effluent products as well as regolith and biological contaminants to scientific sampling sites far away from a lander.*
- Work is underway to **link engineering knowledge and capabilities** (including in rarefied gas dynamics) to best protect and inform future science missions.

See also: Hoey, W., Anderson, J., Alred, J., Soares, C., Gutierrez Cascales, P., Alves Hailer, R. "Modeling the Contaminant Footprint of Spacecraft Operating in Near-Vacuum." 56th Lunar and Planetary Science Conference, The Woodlands, TX; Mar. 2025. [Link](#)

Repurposed from "The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. <https://doi.org/10.48577/jpl.QCQ9TL>

The Contaminant Footprint of Landed Spacecraft: Toward an Inventory and Modelling Framework

Dr. William A. Hoey^{1*}; Carlos E. Soares¹; Dr. John M. Alred²

Abstract: All spacecraft generate and carry contaminants, i.e., unwanted and potentially harmful material. When a spacecraft lands and operates in vacuum, as onto Earth's Moon, it introduces contaminants into its environment that may compromise mission science objectives and engineering performance. Contamination may degrade sites of unique value to planetary science or in situ resource utilization. This presentation will identify and compare source terms and transport vectors for contaminants – in particular, organic material – generated by landed spacecraft. An integrated modeling framework for the organic contamination footprint of spacecraft missions will be described and presented.

1. Amentum Space Missions Division, JETS II Contract, Houston TX.

2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.